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Characterizing arid region soils and vegetation conditions from remotely sensed imagery is limited by low interband and intraspectral reflectance contrast between soil and vegetation. This study has evaluated the spectral response of semiarid soils and vegetation and the utility of four calculated Landsat Thematic Mapper (TM) band ratios and band transformations for discriminating soil and vegetation. Ground-level reflectance spectra were taken of 62 soil and 236 vegetation surfaces. Mean reflectances were calculated for the equivalent TM Bands 1,2,3 and 4. All two-band ratios, the Normalized Difference Vegetation Index (NDVI), and the brightness, greenness, and yellowness transformation were calculated. Soil reflectance spectra are highly variable, yet predictable: They increased directly with wavelength over the visible-near infrared (NIR) region and have low interband contrast. Vegetation spectra are less predictable because various plant structures and phenology affect the spectral response and the visible-to-NIR reflectance contrast. Ration techniques can separate most pure vegetation samples from pure soils, but the degree of separation varies with the technique. Ratioing is effective for surfaces with high interband spectral

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Spectral Characteristics of Selected Soils and Vegetation in Northern Nevada and Their Discrimination Using Band Ratio Techniques

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Characterizing arid region soils and vegetation conditions from remotely sensed imagery is limited by low interband and intraspectral reflectance contrast between soil and vegetation. This study has evaluated the spectral response of semiarid soils and vegetation and the utility of four calculated Landsat Thematic Mapper (TM) band ratios and band transformations for discriminating soil and vegetation. Ground-level reflectance spectra were taken of 62 soil and 236 vegetation surfaces. Mean reflectances were calculated for the equivalent TM Bands 1, 2, 3 and 4. All two-band ratios, the Normalized Difference Vegetation Index (NDVI), and the brightness, greenness, and yellowness transformation were calculated. Soil reflectance spectra are highly variable, yet predictable: They increased directly with wavelength over the visible-near infrared (NIR) region and have low interband contrast. Vegetation spectra are less predictable because various plant structures and phenology affect the spectral response and the visible-to-NIR reflectance contrast. Ratio techniques can separate most pure vegetation samples from pure soils, but the degree of separation varies with the technique. Ratioing is effective for surfaces with high interband spectral contrast but is not effective for surfaces with low contrast. The NIR/red and the NDVI ratios indicate an association with plant-available water gradients and the drought tolerance or drought-avoidance mechanisms.

Introduction

In arid regions, ground-level reflectance spectra (collected in the 400–1100 nm region) of soils, vegetation, and the soil–vegetation mosaic emphasize the difficulty in discriminating between these surfaces. Their separation often is limited by low reflectance contrast between soil and vegetation and between different plant communities. Large variations in soil visible-near infrared reflectance can result from different surface conditions: gravels, precipitated salts, shadows, or plant debris. Vegetation spectra can also be highly variable because of differences in pigmentation, crown cover, growth stage, leaf area, biomass, and shadows.

The visible–near infrared absorptance, reflectance, and transmittance characteristics of the plant will determine those correlations between canopy reflectance spectra and the various plant growth parameters. Leaf pigments, particularly the chlorophylls, are highly absorbant in the visible region (Gates, 1965) and essentially no visible light is transmitted through the plant leaf. In the NIR region, the leaf's absorptance is small and transmission and reflectance tend to be large, which permit reflectances from the surfaces below. These conditions permit high correlations between some spectral data transformation, e.g., band ratios, NDVI, or greenness (Richardson and Wiegand, 1977; Tucker, 1979; Gardner et al., 1985; and Satterwhite, 1984), and the various plant growth parameters, e.g. cover (Satterwhite, 1982), leaf area (Kollenkark, 1982; Holben, 1980; and Best and Harlan, 1985), and biomass (Tucker, 1979; Asrar, 1985; and Elvidge and Lyon, 1985). Also, they are the basis for low

correlations between other transformation and plant parameters.

This paper summarizes ground-level spectral measurements made of vegetation and soil over a 4-year period at 25 sites in northern Nevada and discusses the spectral variations relating to surface conditions. The objective is to analyze semiarid soils and vegetation reflectance spectra and the utility of various transformations of their reflectance in Landsat Thematic Mapper Bands 1, 2, 3, and 4 for discriminating these surfaces.

Materials and Methods

Vegetation and soil spectra were taken in June–July–August of 1981–1984 at 25 sites in northern Nevada; however, not all sites were visited each year. Reflectance spectra were taken of the major plant species and the various soil surface conditions at each site. Most spectra were taken of unstressed, sunlit plant canopies. Some spectra were taken of senesced plants, of shaded soil, shaded vegetation, and wet, sunlit soils for comparison. Shaded soil and vegetation were created by casting a shadow on the surface being measured. The wet soils were created by saturating these surfaces.

The reflectance spectra were recorded over the 400–1100 nm region in 10 nm increments using an EG&G Model 555 spectroradiometer system[1] with a 15° FOV. The surfaces were viewed vertically from a height of 0.5–1.0 m. The spectra were taken on clear, cloud-free days. Shadow effects associated with sunlit plant canopies were minimized by acquiring the spectra between 1000 and 1400 true solar time, i.e., the solar altitude was near its daily peak and the residual shadow effect was not significant (Satterwhite and Rinker, 1986). Reflectance spectra were calculated as the ratio of the sample radiance to the radiance of the halon[1] reference standard [Eq. (1)].

$$\text{reflectance } (\%) = K_x * S_x(i)/H_x(i), \quad (1)$$

where

S_x = Sample radiance at time "x",

H_x = Halon radiance at time "x",

i = 10 nm bandpass,

K_x = solar irradiance correction coefficient.

The K_x value normalizes the reflectance spectra for slight differences in solar irradiance that occur over the daily sampling period. K_x is calculated using

$$K_x = E_{max}/E_x, \quad (2)$$

where

E_{max} is the maximum total short wave solar irradiance during the daily sample period,

E_x is the total short wave solar irradiance at the time the spectra was taken.

The total short wave irradiance (300–3000 nm), was measured with an Eppley PSP Pyranometer.[1]

The reflectance spectra of the soils and each plant species are summarized by a few mean reflectance spectra. Each mean reflectance curve was evaluated using chi-square analyses to ensure it was not significantly different, at the 95% confi-

[1] The citation of commercially available products is not an official endorsement or approval of the use of such products.

TABLE 1 Soil and Vegetation Reflectances for Calculating Brightness, Greenness, and Yellowness Coefficients

	Thematic Mapper Bands (% Reflectance)			
Condition	1	2	3	4
Sunlit, air-dry silt loam	29.57	36.15	41.00	49.02
Sunlit, wet silt loam	10.27	15.55	18.51	26.96
Sunlit, green alfalfa	2.42	5.22	2.56	71.09
Sunlit, senesced, air-dry alfalfa	8.15	13.06	18.04	35.19

dence interval, from spectra that it represents.

The sample's mean reflectance values for Landsat TM Band 1 (blue: 450–520 nm), TM Band 2 (green: 520–600 nm), TM Band 3 (red: 630–690 nm), and TM Band 4 (near infrared: 760–900 nm) are the means calculated across the bandpass. No adjustments are made to approximate the TM sensor values.

Correlations between soil and vegetation reflectance in any two bandpasses are evaluated using linear regression analysis. Using Eq. (3), band ratios are calculated for all TM band combinations where Band A is the longer wavelength.

$$\text{band ratio} = \text{Band A}/\text{Band B}. \qquad (3)$$

The Normalized Difference Vegetation Index (NDVI) ratio is calculated using the mean reflectance values in TM Band 3 and TM Band 4:

$$\text{NDVI} = (\text{Band 4} - \text{Band 3}) / (\text{Band 4} + \text{Band 3}). \qquad (4)$$

The orthogonal transformations of brightness, greenness, and yellowness are calculated for each soil and vegetation surface using procedures described by Jackson (1983) and the reflectances of the soil and vegetation conditions given in Table 1. Coefficients of these indices are used to calculate the brightness, greenness, and yellowness values for each sample (Table 2).

Description of Landform–Vegetation Associations

The field sites are located on mid to lower alluvial fans, river terraces, and valley bottoms. Major soil surface conditions on these landforms are bare soil, gravels, precipitated salts, and salt crust. At some sites, several of these surfaces can occur over a short distance. The texture of these soil surfaces (0–15 cm depth) are sandy loam (SaLm), loam (Lm), clay loam (ClLm), silty clay loam (SiClLm), silt loam (SiLm), silty clay (SiCl), sandy clay loam (SaClLm), or clay (Cl). Saline soils had

TABLE 2 Brightness, Greenness, and Yellowness Coefficients

	Thematic Mapper Bands			
Index	1	2	3	4
Brightness	0.4563	0.4870	0.5317	0.5215
Greenness	−0.2184	−0.2735	−0.3952	0.8493
Yellowness	−0.4721	−0.4593	0.7483	0.0798

Orthoganality = −0.00000078

TABLE 3 Soil and Vegetation Surfaces and Their Reference Numbers

Reference Number	Common Name	Specific Name	Number of Spectra	General Color
1	soil		62	variable
2	moss		5	gray to black
3	cheatgrass	*Bromus tectorum*	5	tan
4	alkali sacaton	*Sporobolus airoides*	4	blue-green, tan
5	sagebrush	*Artemisia tridentata*	38	gray
6	shadscale	*Atriplex confertifolia*	39	gray
7	seepweed	*Suaeda* sp.	3	dark blue-green
8	iodinebush	*Allenrolfea occidentalis*	8	grayish green
9	crested wheatgrass	*Agropyron desertorum*	2	blue-green, tan
10	antelope bitterbrush	*Purshia tridentata*	2	dark green
11	willow	*Salix* sp.	4	gray
12	greasewood	*Sarcobatus vermiculatus*	46	yellow-green
13	rabbitbrush	*Chrysothamnus nauseosus*	15	blue-gray, green
14	salt cedar	*Tamarix* sp.	2	dark green
15	western wheatgrass	*Agropyron intermedium*	4	blue-green, tan
16	saltgrass	*Distichlis stricta*	10	blue-green, green
17	cattail	*Typha* sp.	2	dark green
18	sedge	*Carex* sp.	7	dark green, green
19	bluegrass, timothy	*Poa* sp., *Phleum pratense*	11	green
20	thermopsis	*Thermopsis montana*	2	green
21	alfalfa	*Medicago* sp.	27	green
		Total	298	

electrical conductivities greater than 4.0 mmhos/cm at 25° C. Highly saline soils had surfaces with precipitated salts either as white powderlike materials or as a soft crust. These are found on the valley bottoms, lower alluvial fans, river terraces, floodways, sinks, and low areas where the soils are wet most of the time or the ground water is near the surface. Other saline soils, as well as nonsaline soils, are found on the mid- and upper-level alluvial fans. Soil surfaces, densely mantled with dark-toned gravels varying in size from 0.2 to 10 cm, are found primarily on the alluvial fans.

Vegetation is composed mostly of shrub and grass communities, although some small trees occur on low-lying areas and along the stream banks. The distribution of small trees, shrubs, grasses, and graminoid species varies with plant available water and soil salinity. A listing of the plant species is provided in Table 3. Willow, salt cedar, cattail, and sedge occur on the river floodways and along drainageways, where the water table is near the surface. The wet meadows and pastures had intermediate wheatgrass, saltgrass, and alkali sacaton on saline soils, and bluegrass, timothy, thermopsis, sedge, and cattail on nonsaline soils. Greasewood, saltgrass, iodinebush, salt cedar, and alkali sacaton occur on low-lying, wet saline soils, where ground water is near the surface. Cryptogams, e.g., moss, are found on some saline soils on the river floodplain and on the lower alluvial fans. Once the vadose water is depleted, the soils of the mid to upper alluvial fans are droughty most of the summer. Shadscale, rabbitbrush, and seepweed occur on the saline alluvial fan soils. Sagebrush, antelope bitterbrush, rabbitbrush, cheatgrass, and crested

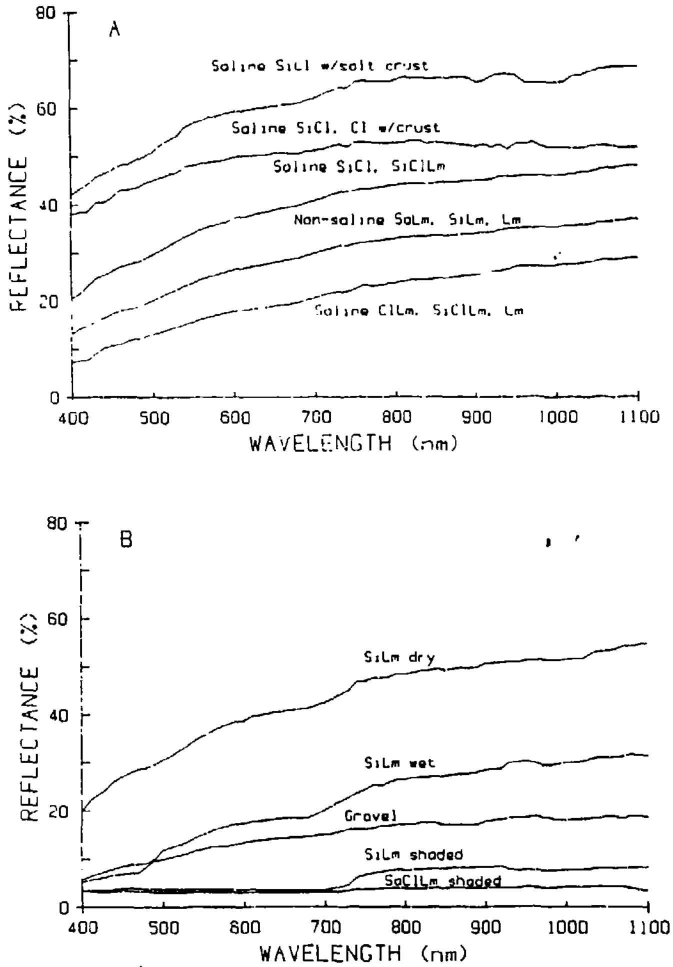

FIGURE 1. Spectra of sunlit and shaded soils.

wheatgrass are found on the nonsaline soils of these fans. Alfalfa is grown on irrigated nonsaline soils on the mid to lower portions of the alluvial fan.

Results and Discussion

The soil and plant species are listed in Table 3, with the number of spectra taken of each surface. The reference number assigned to each surface, corresponds with the figure number that shows the spectra of the surface. The reference numbers also identify each surface in the Figs. 23, 24, and 25.

Reflectance spectra

The 62 soil reflectance spectra taken of the soil surfaces are summarized in Fig. 1. The reflectance of all soils increased directly with wavelength over the visible-NIR spectrum, although the surface conditions were highly variable. The direct relation between wavelength and soil visible-NIR reflectance is described by linear

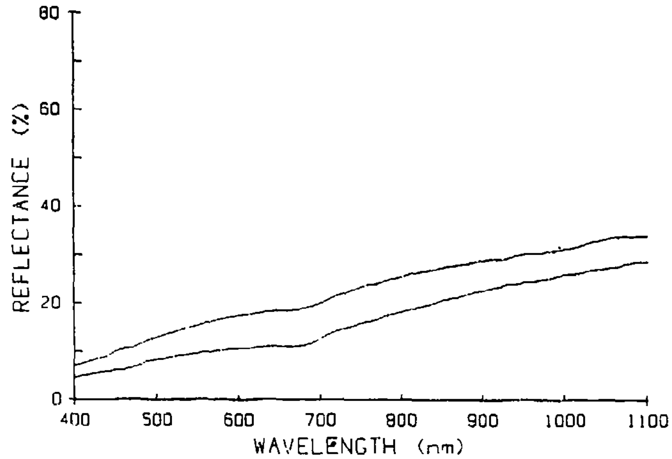

FIGURE 2. Spectra of senesced, dry moss.

regression equation for each spectra in Fig. 1 (Table 5). The dark toned surfaces, e.g., shaded soil and gravel-covered soils have low, relatively flat reflectance curves. The bare fine-grained soils have intermediate reflectances, and saline soils with salt precipitates or salt crusts are highly reflective. Some saline soils have intermediate reflectance curves, resulting from slightly indurate crusts that have incorporated darker silt particles. The effect of moisture on soil reflectance is shown by the spectra of the sunlit, wet silt loam. When wet, this soil surface is less reflective than when it is air dry.

The 236 reflectance spectra of 20 plant species are summarized in Figures 2–21. Generally, these spectra divide the plant species into four groups: green-colored plants, yellow–green colored plants, gray-colored plants, and senesced vegetation. Alfalfa, is characteristic of most green-colored plants, e.g., low reflectance in the blue and red regions, a small peak

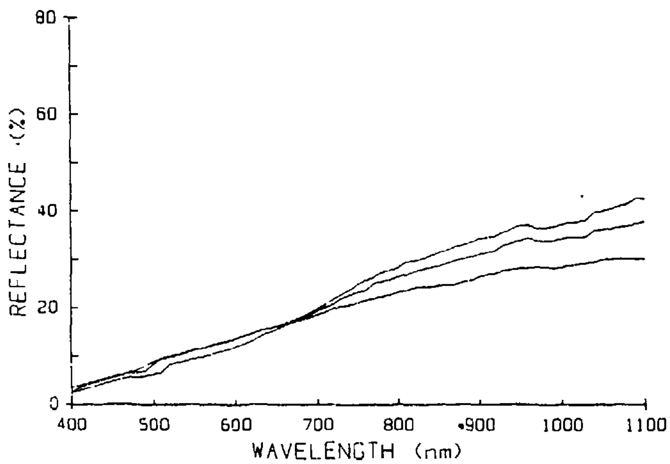

FIGURE 3. Spectra of senesced, dry cheatgrass.

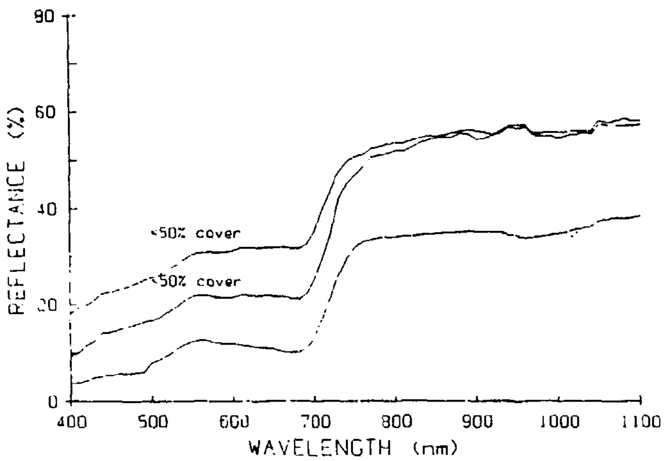

FIGURE 4. Spectra of alkali sacaton.

in the green, then high NIR reflectance (Fig. 21). The yellow–green vegetation, e.g., greasewood, is slightly more reflective in the blue and red regions than the green vegetation, and can be slightly less reflective in the NIR region (Fig. 12). The gray-colored semiarid plants are characterized by a rather flat spectral curve in the visible region and low NIR reflectance, e.g., sagebrush (Fig. 5). The reflectance of senesced vegetation, e.g., straw colored grass or alfalfa, and dark gray to black-colored moss (soil cryptogams) varies directly with wavelength (Figs. 2, 3, and 21); and are described by regression equations (Fig. 5).

The dynamic range of visible reflectances, 3–20%, and NIR reflectances, 20–73%, show that various factors are having substantial effects on these spectra. Shadowing, percent vegetation ground cover, growth stage, and leaf area are just some factors responsible for the widely variable spectra of all vegetation

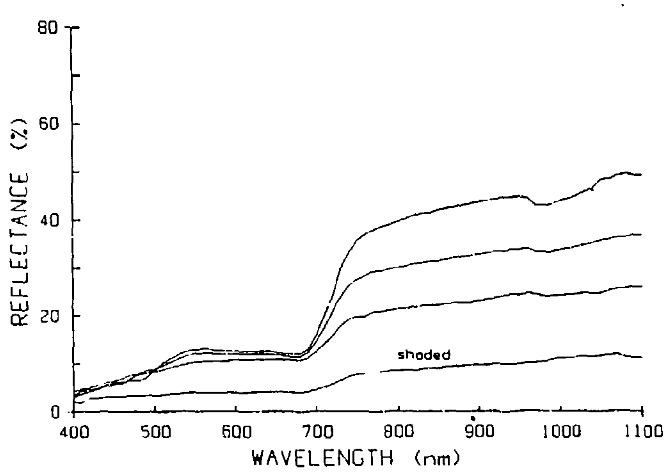

FIGURE 5. Spectra of sagebrush.

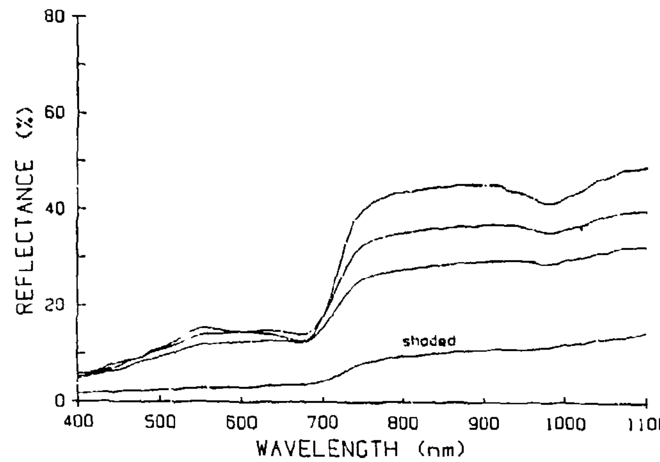

FIGURE 6. Spectra of shadscale.

surfaces. The spectra of artificially shaded sagebrush, shadscale, and greasewood are quite low and are similar to the spectra of shaded soil (Figs. 1, 5, 6, and 12).

The effect of vegetation ground cover is seen in the spectra of those plant species that have substantial differences in their visible reflectances. Species, whose canopies are near 100% ground cover, usually have small differences between their visible reflectances, regardless of their pigmentation, e.g., sagebrush or alfalfa. Species exhibiting variable visible reflectance usually indicate variable ground cover between samples, e.g., alkali sacaton, wheatgrass, and saltgrass. The reflectances of these soil–vegetation surfaces will vary directly with the percentages of vegetation and soil in the radiometer's FOV and the reflectance contrast between the vegetation and soil (Satterwhite and Henley, 1982).

NIR reflectance of most species is variable even for canopies with 100% cover.

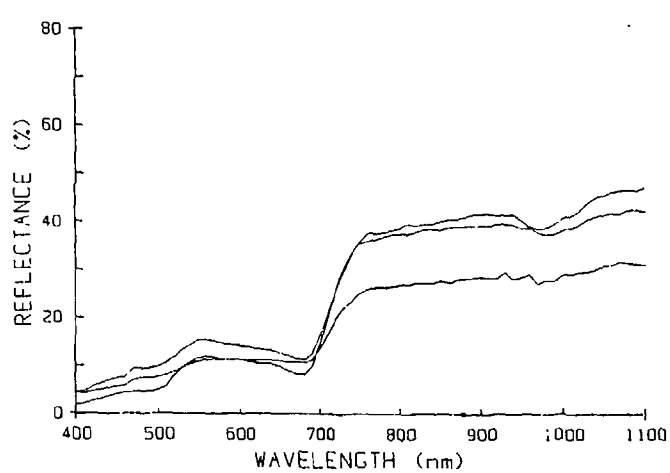

FIGURE 7. Spectra of seepweed.

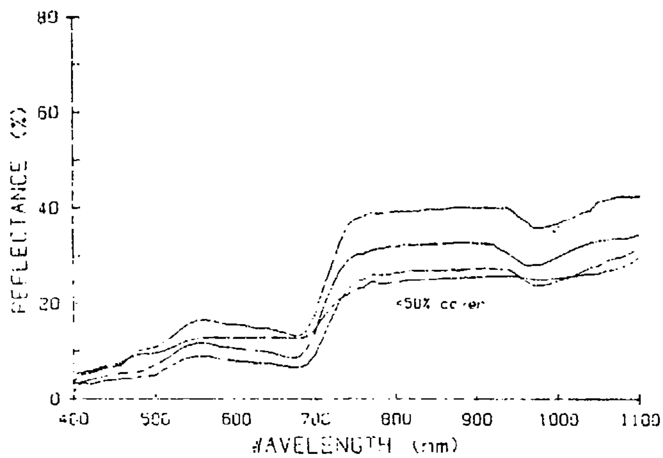

FIGURE 8. Spectra of iodinebush.

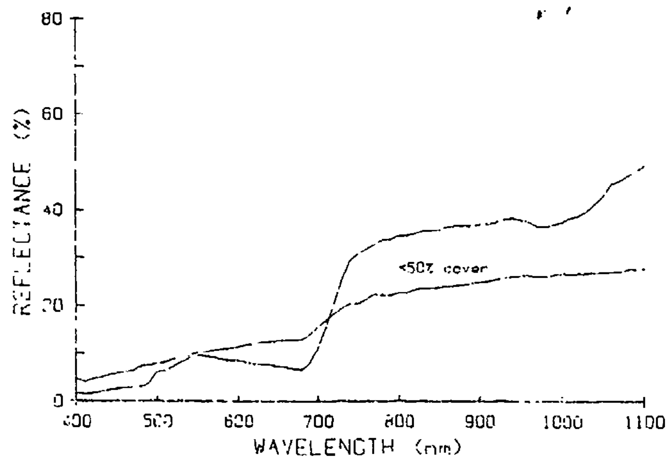

FIGURE 9 Spectra of crested wheatgrass.

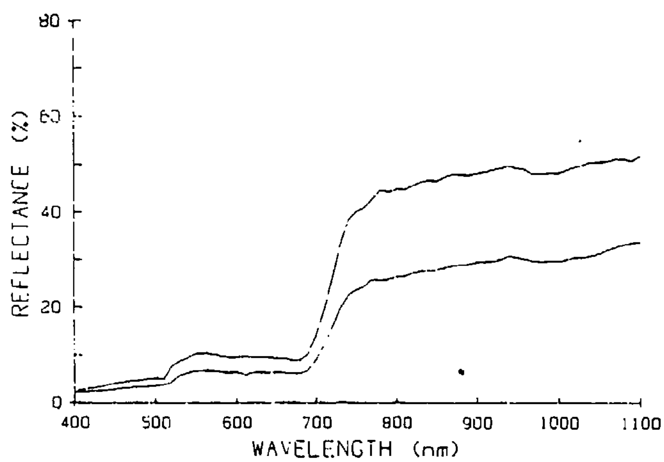

FIGURE 10. Spectra of antelope bitterbrush.

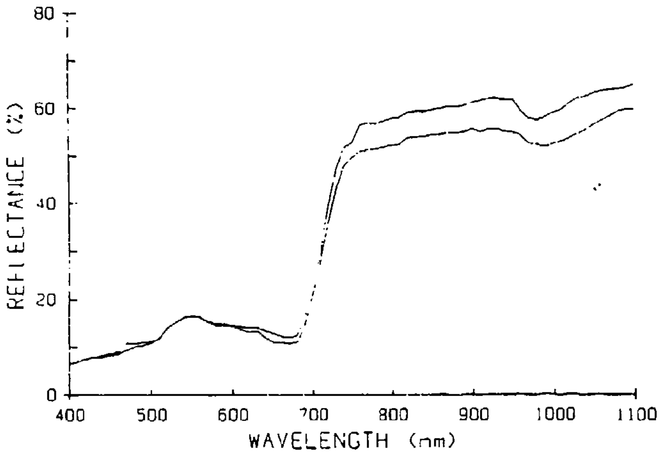

FIGURE 11. Spectra of willow.

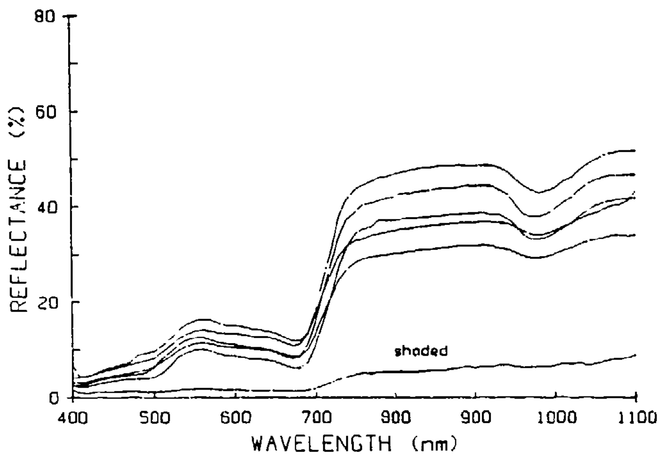

FIGURE 12. Spectra of greasewood.

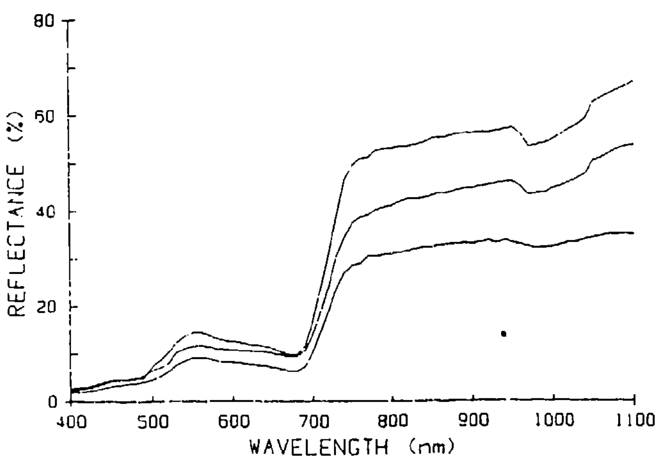

FIGURE 13. Spectra of rabbitbrush.

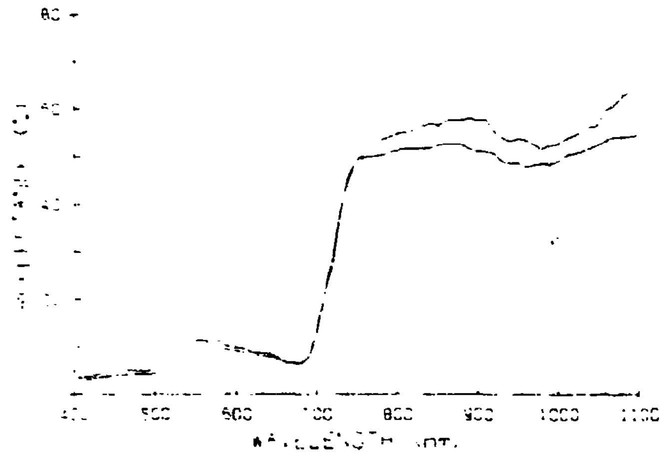

FIGURE 14 Spectra of salt cedar

This is usually a function of several factors: percent canopy cover, the canopy "green leaf" area, and soil background (Huete, 1985). For example, the three spectra of green alfalfa in Fig. 21 have essentially the same visible reflectance, indicating no difference in the ground cover, which is greater than 90% for each sample. The highest NIR reflectance is associated with an alfalfa canopy, greater than 50 cm tall, the moderate NIR reflectance with a 40 cm tall canopy, and the lower NIR reflectance with an alfalfa canopy less than 30 cm tall. The NIR reflectance-plant height relation is highly suggestive of the direct relations between NIR reflectance and leaf area or green biomass, which has been described previously (Tucker et al., 1979; Satterwhite, 1984; and Gauseman et al., 1976).

All physiologically active plants have substantial contrast between their visible and NIR reflectance. The senesced plants have low reflectance contrast, i.e., com-

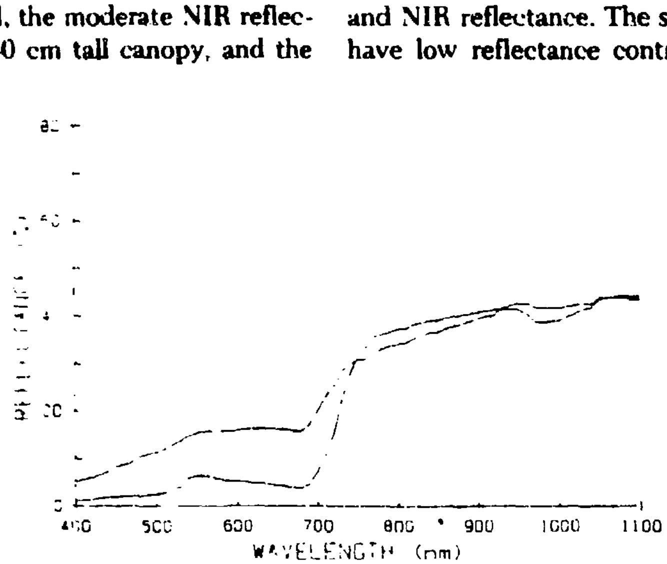

FIGURE 15 Spectra of wheatgrass.

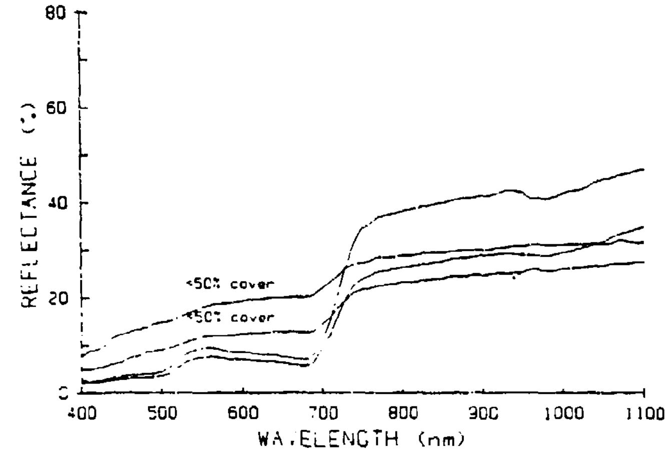

FIGURE 16. Spectra of saltgrass.

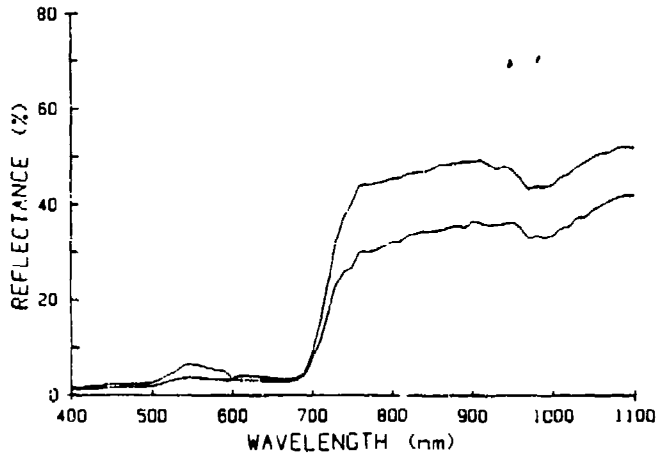

FIGURE 17. Spectra of cattail.

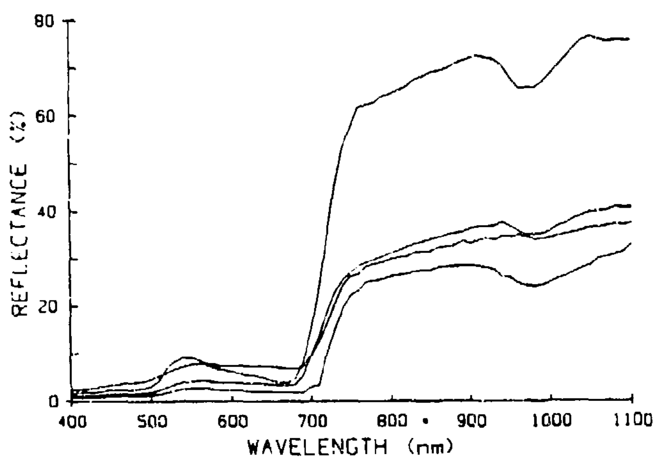

FIGURE 18. Spectra of sedge.

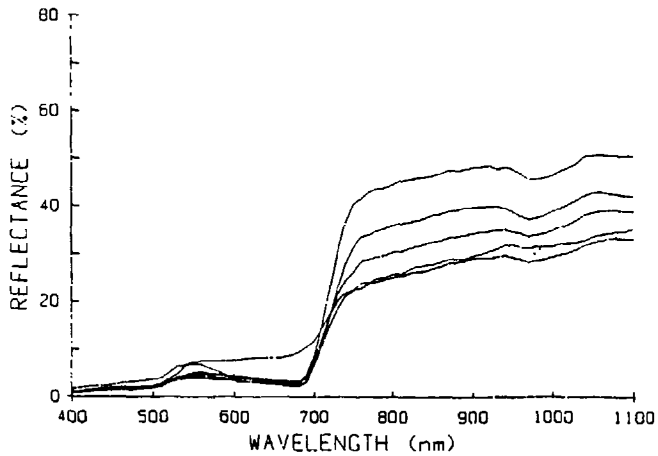

FIGURE 19. Spectra of bluegrass/timothy.

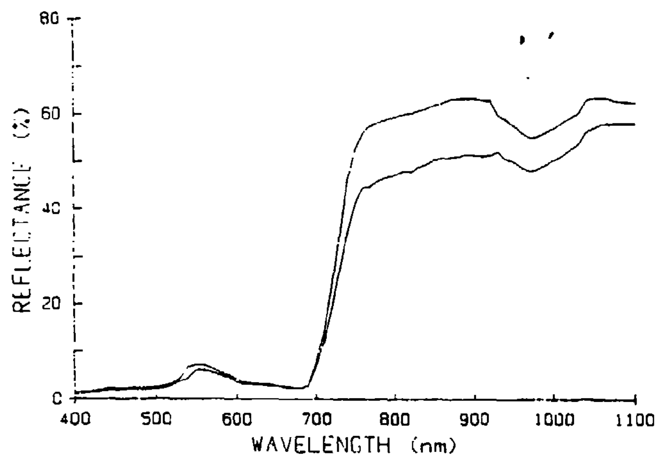

FIGURE 20. Spectra of thermopsis.

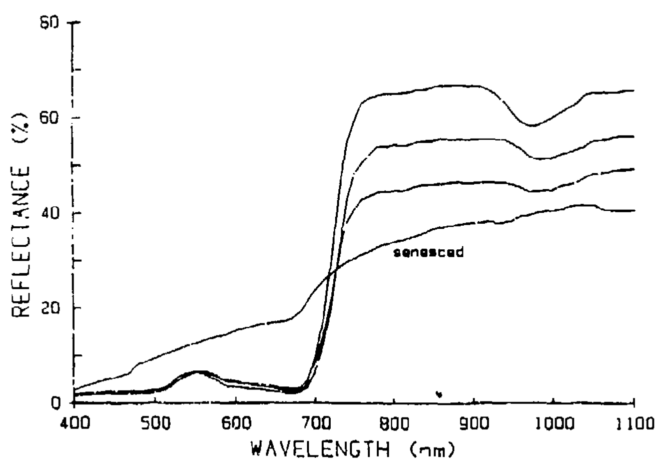

FIGURE 21. Spectra of alfalfa.

TABLE 4 Summary of Band Ratios and Spectral Data Transformations[a]

	Thematic Mapper Band Ratios						Transformations			
	2/1	3/1	4/1	3/2	4/2	4/3	NDVI	BR	GR	YE
					Soil ($n = 62$)					
Minimum	0.97	0.91	1.22	0.94	1.10	1.04	0.02	6.46	−5.82	−6.96
Mean	1.27	1.49	1.83	1.17	1.44	1.22	0.10	35.18	2.01	−0.01
Maximum	1.52	1.97	3.12	1.33	2.18	2.33	0.40	120.26	9.23	2.78
r-Value	0.99	0.98	0.95	0.99	0.97	0.98				
					Vegetation ($n = 236$)					
Minimum	1.16	0.90	1.92	0.45	1.52	1.30	0.13	5.36	3.10	−3.10
Mean	1.45	1.28	7.59	0.75	4.05	5.65	0.50	34.20	20.30	−0.39
Maximum	2.69	2.73	35.1	1.64	22.0	30.43	0.94	72.79	53.88	4.73
r-Value	0.96	0.95	−0.10	0.95	−0.01	−0.20				

[a]TM-1 (450–520 nm); TM-2 (520–600 nm); TM-3 (630–690 nm); TM-4 (760–900 nm) NDVI = (Band 4 − Band 3)/(Band 4 + Band 3); BR = brightness; GR = greenness; YE = yellowness.

TABLE 5 Regressions Describing Soil and Selected Vegetation Spectra

	Soil Spectra	
Saline ClLm	$Y = -18.6 + 0.0801X - 0.000034X^2$	$R^2 = 0.996$
Non-saline SaLm	$Y = -21.7 + 0.111X - 0.000054X^2$	$R^2 = 0.993$
Saline SiCl	$Y = -20.5 + 0.134X - 0.000067X^2$	$R^2 = 0.988$
Saline SiCl	$Y = 6.32 + 0.107X - 0.000061X^2$	$R^2 = 0.957$
Saline SiCl	$Y = -2.30 + 0.146X - 0.000076X^2$	$R^2 = 0.970$
Gravel	$Y = -18.3 + 0.075X - 0.000038X^2$	$R^2 = 0.985$
Dry SiLm	$Y = -25.4 + 0.147X - 0.0000688X^2$	$R^2 = 0.991$
Shaded SiLm	$Y = -1.38 + 0.010X - 0.000000523X^2$	$R^2 = 0.782$
Wet SiLm	$Y = -29.0 + 0.103X - 0.0000431X^2$	$R^2 = 0.991$
Shaded SaClLm	$Y = 2.64 + 0.00042X + 0.00000095X^2$	$R^2 = 0.683$
	Shaded Vegetation	
Sagebrush	$Y = -3.39 + 0.0120X + 0.00000224X^2$	$R^2 = 0.945$
Shadscale	$Y = -4.49 + 0.0106X + 0.00000630X^2$	$R^2 = 0.947$
Greasewood	$Y = -1.58 + 0.0026X + 0.00000615X^2$	$R^2 = 0.916$
Alfalfa	$Y = -26.6 + 0.0552X - 0.00000240X^2$	$R^2 = 0.812$
	Senesced Vegetation	
Moss 1	$Y = -5.23 + 0.0203X + 0.0000105X^2$	$R^2 = 0.990$
Moss 2	$Y = -15.8 + 0.0656X - 0.0000183X^2$	$R^2 = 0.996$
Cheatgrass 1	$Y = -29.6 + 0.0941X - 0.0000357X^2$	$R^2 = 0.999$
Cheatgrass 2	$Y = -28.7 + 0.0851X - 0.0000217X^2$	$R^2 = 0.994$
Cheatgrass 3	$Y = -32.6 + 0.0879X - 0.0000171X^2$	$R^2 = 0.988$

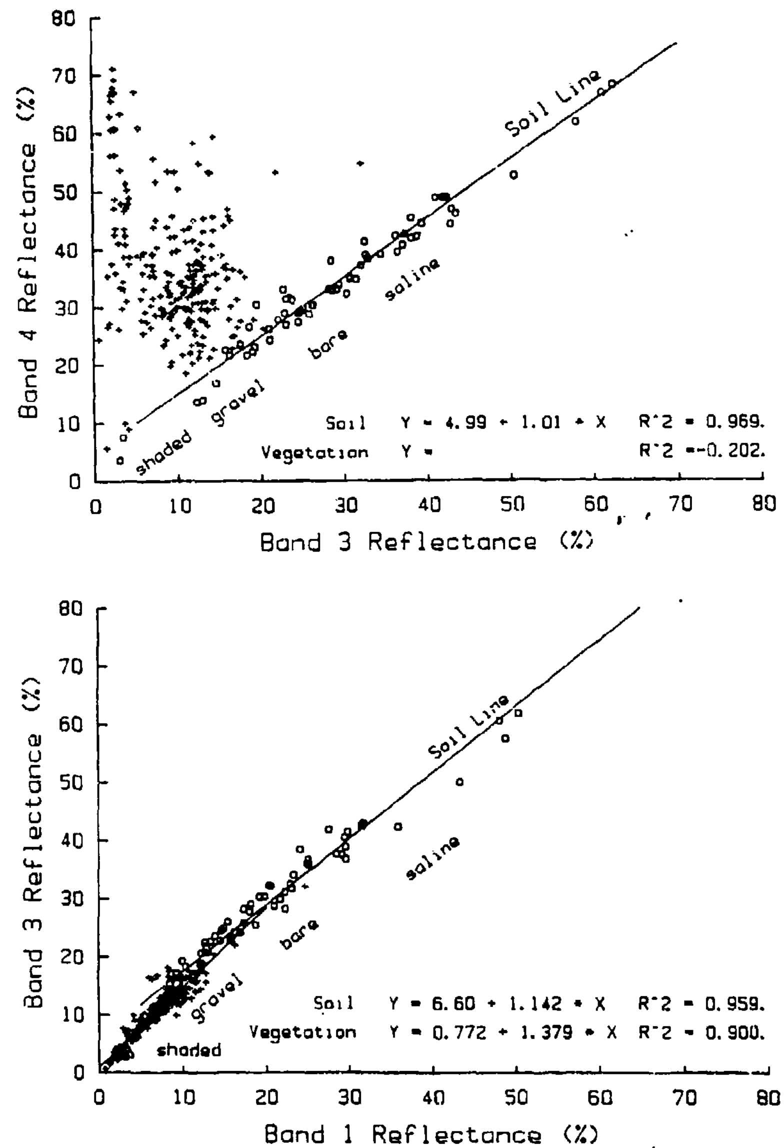

FIGURE 22. Soil (O) and vegetation (+) reflectances in Thematic Mapper Bands 1, 3, and 4.

pare the spectra of the green alfalfa with the straw colored, senesced alfalfa (Fig. 21), the spectra of "active" and dry saltgrass (Fig. 16), or cheatgrass (Fig. 3). The visible to NIR contrast of the plant canopy will vary with the plant's pigmentation, ground cover, and leaf area. The active plants have high reflectance contrast, because of the chlorophyll absorbance in the visible region. Senesced vegetation has lower contrast because of lost chlorophyll pigmentation, which in-

creases visible reflectance and the collapsed internal leaf structure that alters NIR reflectance (Gausman et al., 1970).

Band correlations between all combinations of TM Bands 1, 2, 3, and 4 are summarized in Table 4 by soil and vegetation surfaces. Soil reflectances in any two TM bands are highly correlated, r values > 0.90. The vegetation reflectances in the visible bands are highly correlated, r values > 0.90, but correlations between any visible band and the NIR band are very low, r-values ranging from -0.2 to -0.01. These relations are illustrated in Fig. 22. The high correlations are shown by the distribution of data about the "soil line," while the low correlations for vegetation are depicted by more widely scattered data. The high correlations between band reflectance are predictable in view of the spectral curves in Fig. 1 and the regressions describing these wavelength-reflectance relations (Table 5). The soil surfaces at the lower end of the soil line correspond to shaded or gravel covered soils while those at the upper end are soils with salt precipitates.

Vegetation reflectance in TM Bands 1 and 3, and TM Bands 3 and 4, are typical of the other TM band correlations, which show the differential effects of leaf reflectance, transmittance, and absorptance on the plant's visible and NIR reflectance as affected by cover, leaf area, shadows, and pigmentation. The low correlation between visible and NIR reflectance is expected because these multiple NIR reflectances increase the NIR reflectance, but the high absorptance of visible light keeps the visible reflectance fairly constant.

The reflectances of senesced vegetation and the shaded vegetation varied directly with wavelength and are highly correlated. These strong reflectance–wavelength relations are described by linear regressions (Table 5).

Many plant and soil surfaces often have similar reflectances in some bandpasses, but in other bands these surfaces can be quite different spectrally. The dynamic ranges of soil visible and NIR reflectance usually overlap those for vegetation surfaces. In the visible region, many soils are more reflective than the plants occurring on them, although dark toned gravels, shadows, or wet soils can be similar to some plant surfaces. The NIR reflectance of sunlit vegetation varies widely, with the gray-colored species and senesced vegetation being similar to some light-toned, sunlit soils. The similarities in both the visible and NIR regions have necessitated various spectral data transformations for discriminating the vegetation and soil surfaces. Tucker (1979) and Richardson and Wiegand (1977) evaluated various linear transformations of reflectance spectra or Landsat digital data. Most successful spectral data transformation techniques use the reflectance contrast between the visible and NIR spectral regions. The NIR/red ratio and the NDVI transformations provide "good" separation of agricultural crops and soils (Jackson, 1983), and soil and vegetation differences in rangelands using small scale digital imagery (Heilman and Boyd, 1986). Other simple band : band ratios can be effective discriminants if there is sufficient reflectance contrast between the two bandpasses (Satterwhite, 1984; Hughes et al., 1986).

Spectral data transformations

All two-band ratios of the four TM bands are summarized in Table 4. No

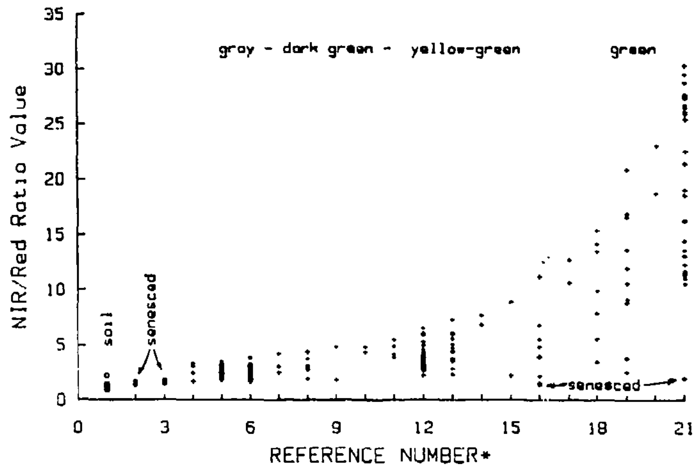

FIGURE 23. NIR/red ratios for soil and vegetation.

ratio completely separates all soils from the vegetation surfaces. These ratios tightly cluster the soils and those plants with low interband reflectance contrast, and the dynamic range of the soil ratios often overlap that of the vegetation surfaces. The visible:visible band ratios illustrate the low interband contrast for both vegetation and soils. The dynamic range of the NIR:visible band ratios is substantially larger than that of the visible:visible band ratios (Table 4 and Fig. 23). The NIR:red ratio is similar to the other NIR:visible band ratios, and it separates the soils and vegetation into three groups: a) soil and senesced vegetation, (ratios less than 2.3); b) gray and yellow–green vegetation (ratios of 2.0 to 7.5); and c) green vegetation (ratios greater than 7.5).

NDVI identifies the same groups as the NIR:red ratios: a) soils and senesced vegetation, NDVI values are less than 0.3; b) gray or yellow–green vegetation,

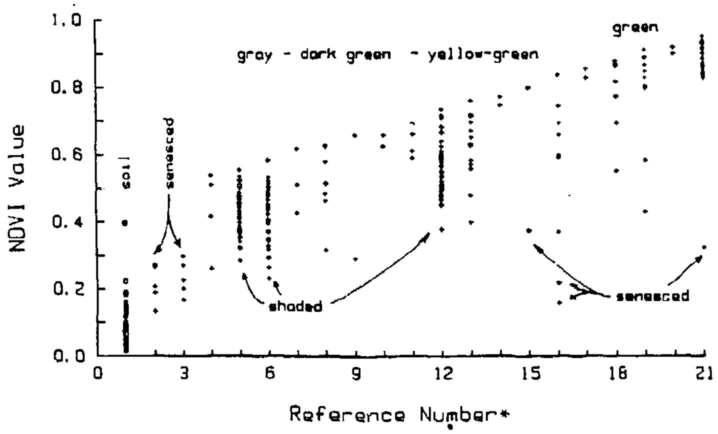

FIGURE 24. Normalized difference vegetation index for soil and vegetation surfaces.

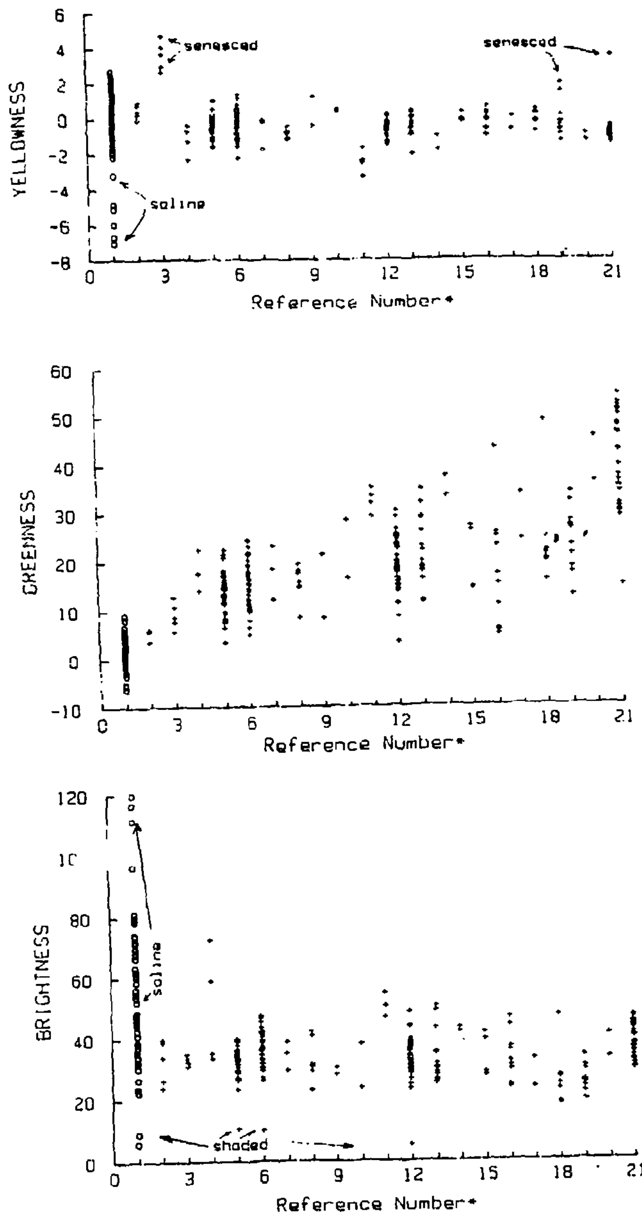

FIGURE 25. Orthoganol transformations of soil and vegetation reflectances in Thematic Mapper bands.

values ranging from 0.3 to 0.7; and c) green vegetation, values greater than 0.7 (Fig. 24).

The NIR:red and NDVI transformations separate the soil and vegetation surfaces according to their visible and NIR reflectance contrast. Species with low NIR:red contrast, e.g., sagebrush had better separation using the NDVI transformation while species with high NIR to red contrast are separated better by the NIR:red ratios, e.g., alfalfa.

In arid regions, the plant's habitat may be indicated by the spectral characteristics of the plant species. Arranging the plant species by their maximum NIR/red ratio show that: a) low ratios are indicative of senesced or gray-colored vegetation that occur on droughty alluvial fan soils; b) intermediate ratios are indicative of yellow–green-colored or blue–green plants that occur on moist saline floodplain soils; and c) high ratios are indicative of green-colored plants that occur in standing water, on wet meadows, or in irrigated agricultural fields. Although these groups are not clearly defined, because of the many factors affecting the canopy reflectance spectra, there are apparent associations between the plant's spectra, its phenology, and the site's environmental factors.

The brightness index discriminated many of the soil surface conditions but did not separate the vegetation from many of the soils (Fig. 25). This index gave good separation of the soil surfaces, low to high values, in a manner very similar to that described by the "soil line" (Fig. 22), while the NIR/red and NDVI transformations tightly clustered the soil surfaces.

The greenness index separates those surfaces with high NIR:visible reflectance contrast, e.g., most vegetation, but it does not separate those surfaces with low visible to NIR reflectance contrast, e.g., soils. The soil greenness index ranged from −5.8 to 9.2. Vegetation with greenness values less than 12 were senesced vegetation (cheatgrass, moss, saltgrass, and alfalfa), shaded vegetation, and some sagebrush, shadscale, or saltgrass surfaces. Physiologically active, sunlit plants with ground covers near 100% had greenness values ranging from 12 to 54.

The greenness index like NIR/red and NDVI uses the reflectance contrast between the TM bands, e.g., interband reflectance contrast. Consequently, those plant factors affecting the contrast are shown in the index value, e.g., plant pigmentation, ground cover, leaf area, and plant growth state. For example, the greenness values calculated for wheat (Jackson, 1983) and soybeans (Kollenkark, 1982) varied with ground cover and leaf area. These factors apparently contribute also to the dynamic range of greenness values for these semiarid species.

The yellowness index only separated the straw-colored, senesced vegetation, e.g., cheatgrass (values greater than 2.0), and the highly saline soils (values less than −3.0). Other soil and vegetation surfaces with indices ranging from −3.0 to 2.0 show no clear separation.

The transformation of mean reflectance data can achieve good separation of soil and most vegetation surfaces, and differentiate individuals within a specific surface type. The NIR:red ratio, NDVI, and greenness index separate the soil and vegetation surfaces according to the reflectance contrast between TM bands. Surfaces with low reflectance contrast often had the similar transform values.

The brightness index achieved good separation among the various soil surfaces, but a separation was not accomplished using the other transformations.

Conclusions

Soil and vegetation reflectance spectra show some surfaces have unique spectra, but discriminating between many surfaces often requires spectral data manipulation procedures. Soil reflectance increased directly with wavelength over the visible-NIR spectrum and had low interband reflectance. Vegetation spectra are highly variable and highly correlated only between the visible TM bands. Two-band ratios and the NDVI are effective when a surface has high reflectance contrast between bands, but they are not effective for surfaces with low interband contrast. The greenness transformations separate most soil and vegetation surfaces. The soil surfaces were differentiated further using the brightness transformation, but brightness by itself could only separate some soils from the vegetation surfaces. The vegetation could be separated into smaller groups using those factors affecting their visible-near infrared spectrum.

The NIR/red, NDVI, and greenness index show promise for identifying the vegetation associations along plant available water gradients and with plant drought tolerance or plant drought-avoidance mechanisms.

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